JUDGMENTS OF THE VISIBILITY OF COLORS MADE FROM AN UNDERWATER HABITAT

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SUMMARY PAGE

THE PROBLEM

To extend previous results on the visibility of colors under water to include viewing from an underwater habitation, in 100 ft of water, at various times of the day.

FINDINGS

Light colors were in general the most visible when viewed against the water background, but dark colors were best against a light gray background. Small diurnal changes in the visibility of orange and green were found.

APPLICATION

Colors can be selected for a wide variety of underwater missions from these and previous results. For example, specific colors are best to conceal objects under water while others can be selected for highest visibility; the latter includes objects which might be inadvertently lost at sea or the choice of color for greatest legibility of directions or underwater coding.

ADMINISTRATIVE INFORMATION

The investigation was conducted as part of Bureau of Medicine and Surgery Research Unit M4306.03-2050DXC5. The present report is Number 17 on this work unit. It was submitted for review on 6 March 1974, approved for publication on 19 March 1974 and designated as NavSubMedRschLab Report No. 777.

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ABSTRACT

Judgments of the relative visibility of colors were made during the "La Chalupa" dive from an underwater habitation located in 100 ft of Caribbean water. Judgments made with colored targets viewed against the water background were in agreement with previous studies; that is, bright colors were the easiest to see and dark colors disappeared the most readily. However, when the colors were viewed against a light gray background, dark colors were the most visible. It appears that negative contrast under water is superior to positive contrast of the same amount. In addition, small diurnal changes were found with green increasing in visibility and orange decreasing as the day wore on.

JUDGMENTS OF THE VISIBILITY OF COLORS MADE FROM AN UNDERWATER HABITAT

INTRODUCTION

The Naval Submarine Medical Research Laboratory has conducted a number of investigations of the visibility of colors under water; the results have shown that the turbidity of the water and the type of illumination are of paramount importance in determining which colors are most and least visible. For example, with natural illumination, in turbid water characteristic of bays and harbors, oranges and reds are most visible while in clear Caribbean waters, blues and greens are most visible.[1] The use of a tungsten light source increases the relative visibility of the reds and a mercury source, the yellow-greens.[2]

These results were obtained with three dimensional objects viewed by SCUBA divers along a horizontal path in the water. Thus, all targets were viewed against a natural water background. We are now testing the generality of the results under a number of different operational conditions. For example, an underwater search mission has been simulated by having divers look for different colored objects scattered over the bottom of a lake; the number of objects of each color retrieved by the divers agreed well with the data on their visibility under water.[3]

The investigation reported here represents a further test under operational conditions: colored targets were viewed from an underwater habitat, at different times of day, during a two-week saturation dive of 100 ft depth off Puerto Rico. Two types of colored targets were employed: one was an array of colored spheres of the same type as had been used in previous studies; the other was a set of flat, light gray targets upon which were painted squares of different colors. The investigation provides data on three questions. First, the daily measures should show whether or not there are significant variations in the most and least visible colors as a function of the time of day under natural lighting conditions. Second, the responses to the colored spheres extend the depth range beyond what has been used previously. Third, the use of a constant background on the flat targets provides data relative to conditions other than a natural water background; its use might be comparable to searching, for example, for objects on a light-colored sand bottom.

PROCEDURE

The two types of colored targets were set up on the ocean bottom so that they could be viewed from the habitat port. The array of four buoyant spheres - each one 20 cm in diameter and painted a different color - was placed 40 ft from the habitat and arranged so that its center was at eye level when viewed from the habitation's port.

The flat surfaces with the squares of color on them were placed on stands so that the flat face of the target was perpendicular to the line of sight from the port. These targets were placed at distances of 32, 48, 64, and 80 ft from the porthole and was constructed of sizes appropriate to subtend the same angle at the eye of the viewer. Diagrams of the underwater layout are shown in Fig. 1.

Each flat target had four different squares of color. The target subtended 2.5 degrees on a side; each colored square was 0.5 degree on a side and was surrounded on all sides by a gray area.

A description of the colors used on all the targets is found in Table I. It was obviously impossible to test all colors at all distances. Therefore, a selection was made on the basis of previous research of particularly important questions or of specific predictions.

1. Black and white were included in each of the arrays, to determine which is more visible and whether this changes with distance.

2. Fluorescent orange has been shown previously to be highly visible in clear water at close distances only; its visibility should deteriorate with greater viewing distances.

3. Green has been shown to be particularly effective in clear water; a comparison was made between fluorescent and regular green.

4. Gray was chosen to typify a poor visibility color.

Among the flat targets, those at 32 and 64 ft had black, white, dark gray and fluorescent orange as the four colors. The other two, at 48 and 80 ft, had black, white, regular green and fluorescent green. On the vertical array of spheres, the colors were, from top to bottom: fluorescent green, white, black, and fluorescent orange.

The aquanauts were provided with data sheets on which to check all the colors they could see and rank each for the ease with which they could see them. Since there were four colors in each array, a rank of one meant the most visible and a rank of four the least.

The main set of observations were made in the "La Chalupa" study at a depth of 100 ft, from April 26 through May 5, 1973. Four different divers made observations, when free to do so, several times each day: in the early morning, around noon, and in the mid-and late afternoon. Additional observations were made in the second study in 50 ft of water, from June 19 to 28, 1973. Only the spherical targets were used at this depth; they were placed at a distance of 25 ft from the habitation since the water was more turbid in the new location, and judgments at this time, early in June, were also possible very early in the morning.

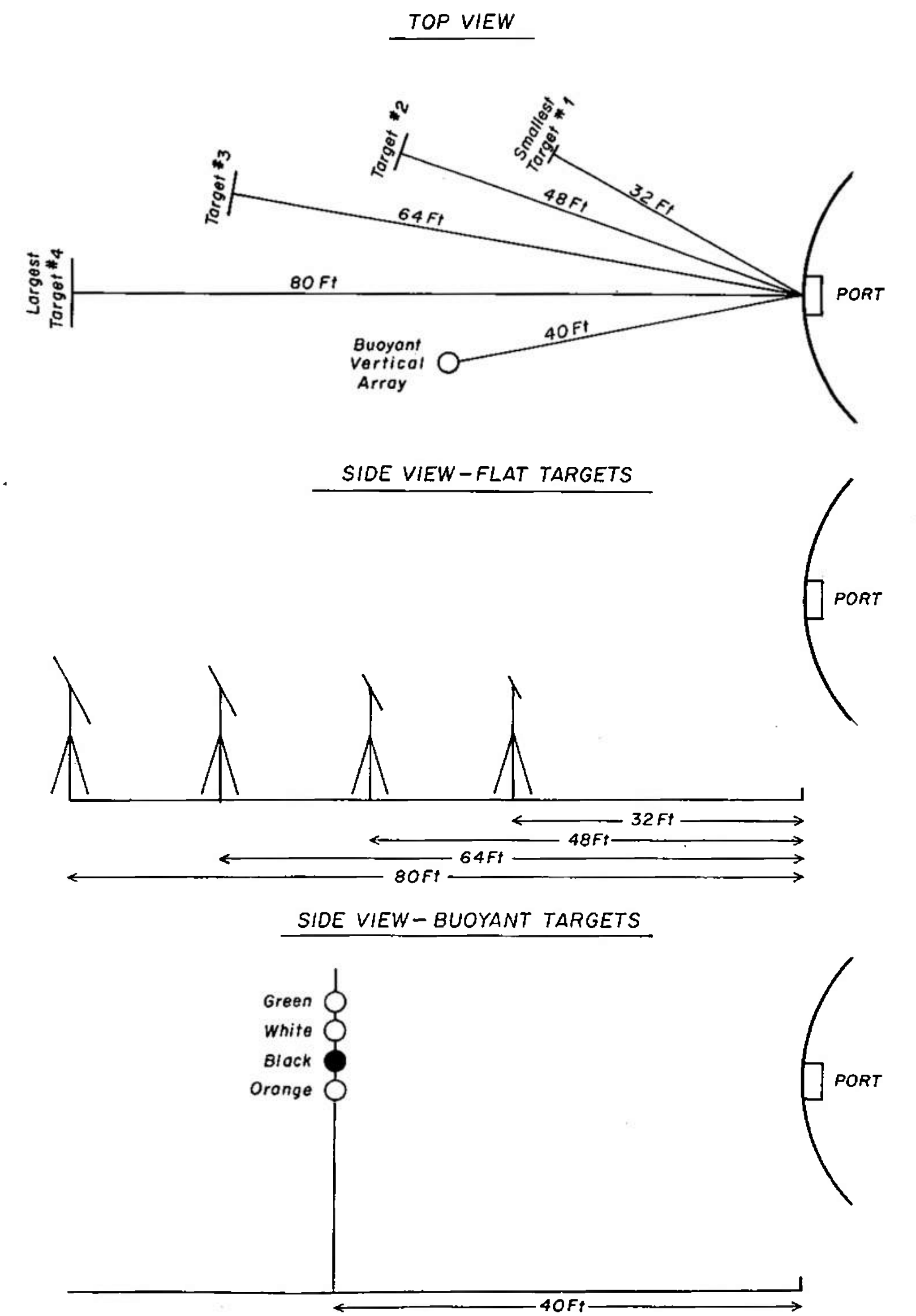

Fig. 1. Diagram of the arrangement of targets under water: (a) top view of the entire array, (b) side view of the flat targets, and (c) side view of the spherical arrangement.

Table I. Specification of Paints Used on Targets

Color	Reflectance	C.I.E. Chromaticity Coordinates		
		x	y	z
Fluorescent green	80.0[a]	.2625	.6005	.1370
Fluorescent orange	97.0[a]	.5558	.4183	.0258
Regular green	10.2	.2966	.4619	.2414
White	79.6	.3128	.3241	.3629
Dark gray	20.0	.3197	.3325	.3477
Black	5.0	.3101	.3163	.3736
Light gray background	44.0	.3060	.3147	.3792

[a] Approximate value when activated by full sunlight.

RESULTS

Spherical Targets

Judgments of the relative visibility of the four spheres were available from two dives, one at 100 ft depth and 40 ft viewing distances and the other 50 ft depth and 25 ft distance. The mean ranks for both conditions are given in Table II. Despite the difference in depth, the major results were the same; that is, white and fluorescent green were the most visible colors and black the least visible, at all times of day.

Since depth was not an important factor in the visibility of the colors, the data were combined and are shown in Fig. 2. The mean visibility ranks are the same as Table II, with white and green most visible and black the least. In addition, the figure shows small diurnal changes: fluorescent orange was most visible early in the morning and got worse as the day progressed, while fluorescent green showed the reverse pattern, improving as the day wore on. The changes in black and white were minor and probably simply reflect the differences in the two fluorescents, since all judgments were relative.

Table II. Mean Ranks of the Visibility of Spherical Targets during the Day

Time of Day	Depth - 100 ft					Depth - 50 ft				
	Fluor. Green	White	Black	Fluor. Orange	N	Flour. Green	White	Black	Fluor. Orange	N
0600-0730						2.20	2.00	3.40	2.40	5
0800-1000	1.95	1.80	3.92	2.32	20	2.19	1.44	4.00	2.44	16
1100-1400	1.69	1.85	3.92	2.54	13	2.91	1.27	3.95	2.86	11
1500-1730	1.67	1.78	4.00	2.56	9	1.67	1.33	4.00	3.00	3
1800-1900	1.33	2.17	4.00	2.50	6	1.50	1.50	3.25	3.75	4
Overall Mean	1.75	1.85	3.95	2.45	48	1.97	1.46	3.83	2.75	39

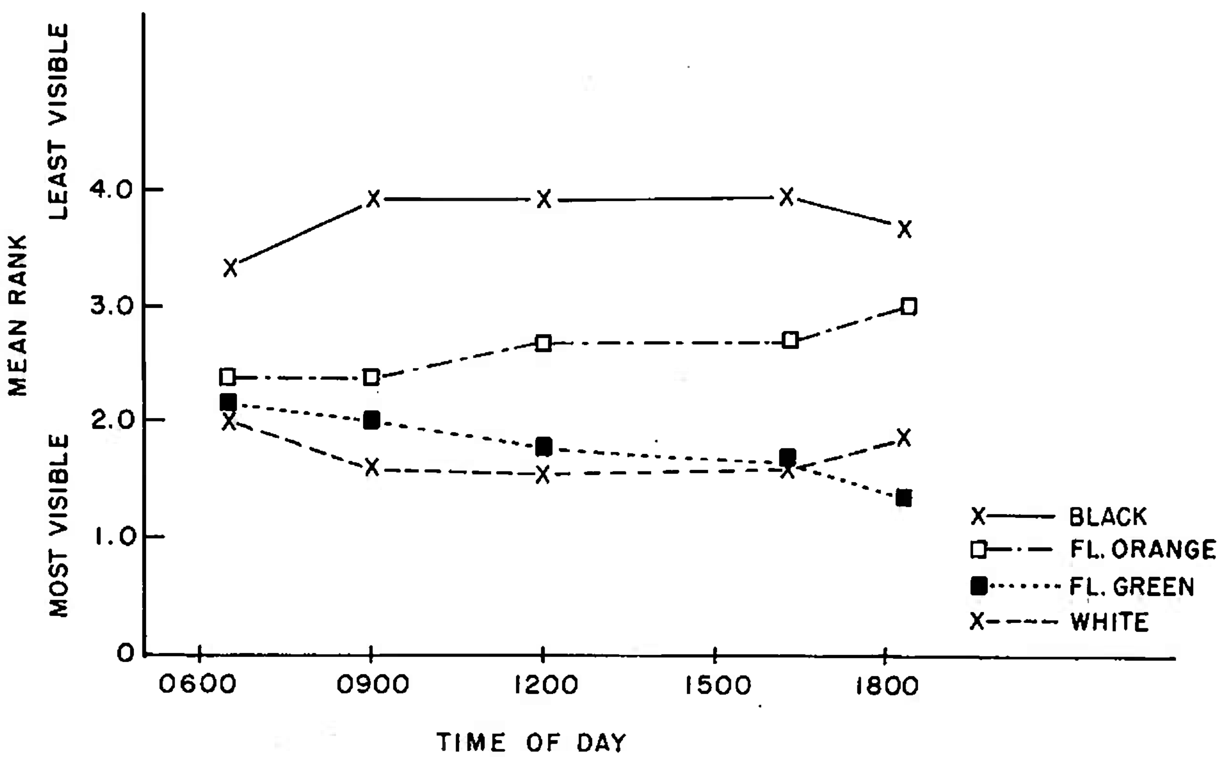

Fig. 2. The relative visibility of the spherical targets at various times during the day.

One small difference is apparent in the comparison of data in Table II; the fluorescent colors were poorer in general during the 50 ft dive than at 100 ft. Since the 50 ft dive occurred after the 100 ft, the most likely explanation is that the fluorescent material was wearing out. Indeed, evidence of this can be found in the first dive; Figure 3 shows the mean ranks plotted temporally; both fluorescent colors got worse over the course of the dive. At the end of the 100 ft dive, the mean rank of both was almost identical to their score in the 50 ft dive. The same evidence of deterioration was found in judgments of the fluorescents on the flat targets.

The visibility data for the colors on the flat targets are summarized in Fig. 4. Several comparisons are possible. Fluorescent colors again rank well, as they did on the spherical targets. However, a major reversal has occurred in the visibility of black and white. Against the gray background, white is now one of the least visible colors, and black, with one exception, is the most visible.

Comparison of the visibility of the same color at two different distances reveals two reversals. Fluorescent orange is more visible than black at 32 ft and less visible at 64 ft. This was, of course, predicted; at near distances the orange has the advantages of both brightness and color contrast, but at far distances the long wavelengths are absorbed by the water. Another interesting reversal occurs between the white and gray - white being more visible at 32 ft and gray at 64 ft.

In general, the colors retain their relative ranks throughout the day; there are few consistent diurnal changes. Fluorescent green does show the small improvement during the course of the day that was found with the spherical targets. Since diurnal changes were small, the data at different times were combined and are shown in Fig. 5 as a function of distance. A comparison of Fig. 5 with Figs. 2 and 3 shows again the dramatic reversal in relative visibility of black and white.

DISCUSSION

Several of the results on the relative visibility of colors under water are deserving of comment. First, diurnal changes were small but, in general, the visibility of green improved during the day and visibility of orange deteriorated. Second, for targets viewed against the water background, the bright colors were the best (i.e., white, and fluorescents), but for targets viewed against the constant light gray background, black was superior and white, poorest. And, finally, there was some evidence that the fluorescent colors deteriorated over time.

Diurnal Variations

There are many possible reasons for the change in the relative visibility of green and orange during the day, such as variations in the spectral energy distribution of sunlight and changes in the spectral absorption of the water. The largest diurnal change in the spectral energy distribution of sunlight is a shift towards the longer wavelengths as the sun nears the horizon; this is due to greater

scattering of short wavelengths by the air molecules as the energy travels through different amounts of air mass.[4] Since there is no evidence of a symmetrical change in the visibility of colors from, for example, 6:00 AM to noon to 6:00 PM, changes in spectral energy distribution can be discounted as a cause of these shifts.

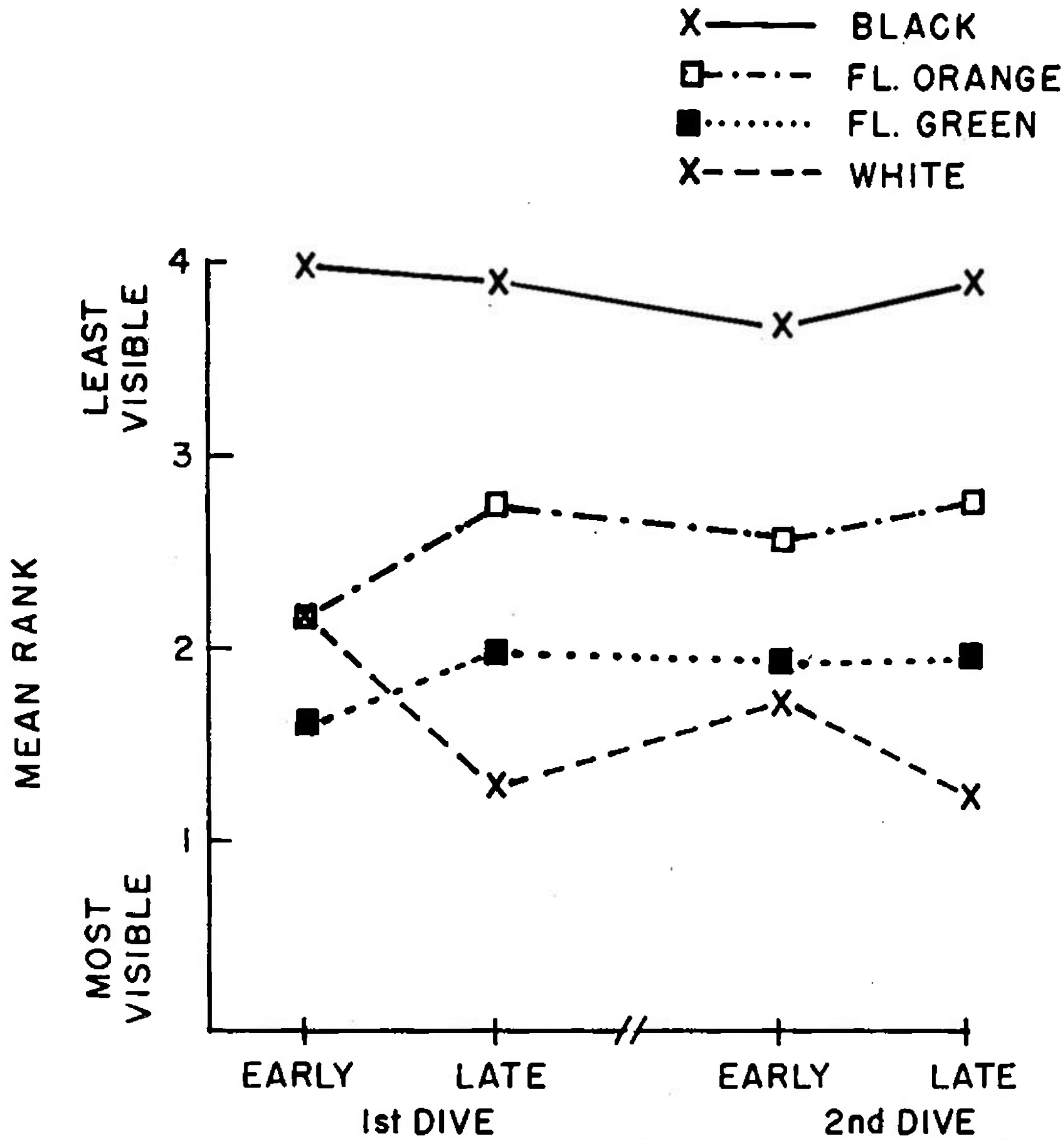

Fig. 3. Changes in the relative visibility of the spherical targets over the course of the two dives.

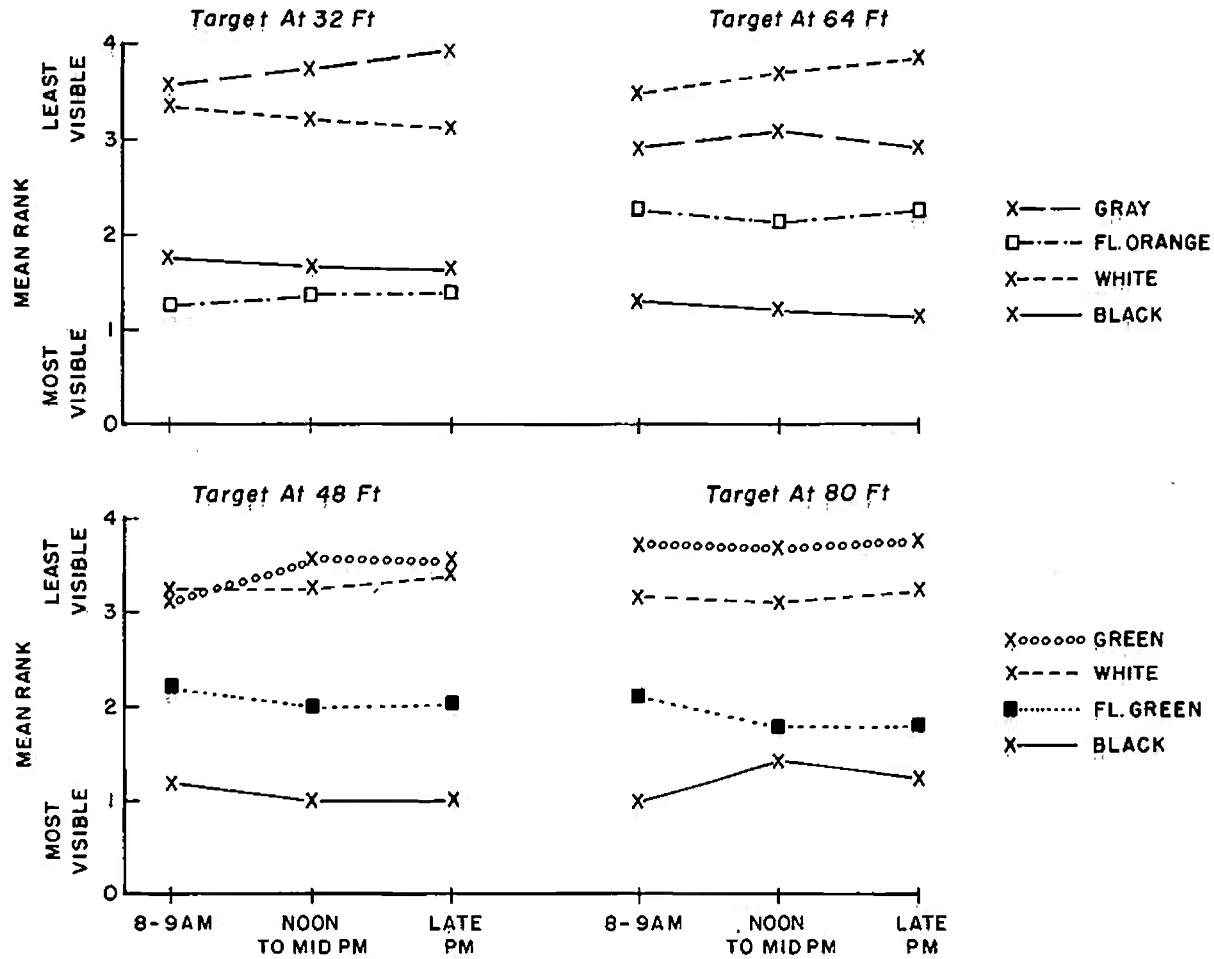

Fig. 4. The relative visibility of colors on the flat targets at different distances during the course of the day.

Changes in the particulate matter in the water, due to differences in current velocity and direction, the presence of plankton in the water, and perhaps to the activities of the divers themselves, therefore seem the most reasonable cause. In fact, one of the divers observed that the water appeared cleaner and bluer early in the morning than during the rest of the day. This observation would relegate the changes in visibility of orange and green to differences in contrast of the colors against the blue background rather than to differences in brightness contrast.

The Effect of Contrast

The judgments of the relative visibility of the spherical targets are in

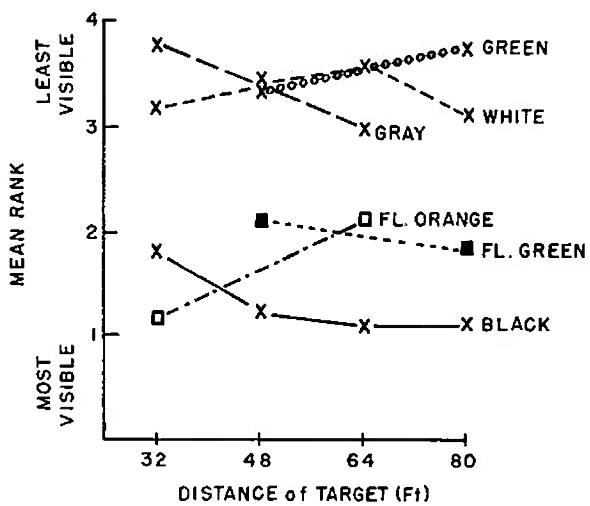

Fig. 5. Average data of the visibility of the different colors on the flat targets as a function of viewing distance in the water.

complete agreement with all of our previous studies in which targets are viewed against a water background. In general, these show that the darker the color, the poorer the visibility; this is due to the lack of brightness contrast with the dark water background. A color can appear dark for two reasons; either it is inherently dark, such as dark gray or black, or the wavelengths it reflects are not transmitted by the particular body of water. Examples of the latter are the appearance of red, which looks black when viewed through any sizeable distance of clear water, and the loss of visibility of fluorescent orange with distance in water. In both cases the long wavelengths are markedly attenuated by the increased distance of water through which they travel with a resulting loss of brightness.

These data can be predicted from calculations of the contrast between the brightness of the object through the water and the brightness of the water background. In fact, there are formulae available for such calculations based upon the absorption and scattering characteristics of the particular body of water, the angle of view, and the distance of the object.[5-7] The formulae are in agreement with these data for a horizontal viewing path against a water background; furthermore, they predict similar results for a downward viewing path against a water background. In the case of looking straight upward, there is essentially no difference in the visibility of colors since all appear as silhouettes against the lighted background.[8]

The judgments of the visibility of colors on the flat targets were made in an attempt to utilize a background lighter than the normal water background. A light gray was chosen for the background of all colors, and this change produced some interesting results. These are illustrated in Table III in which the judgments of visibility in the water are compared to similar judgments of the same colors in air on a sunny day. The air judgments conform well to the relative contrasts; targets with the greatest contrast are judged most visible, regardless of whether the contrast is negative or positive. Some of the differences between the air judgments and those in the water were expected, as for example, the change in visibility of fluorescent orange with distance under water, already referred to.

Table III. Average Ranks of Visibility of Colors on Flat Targets

Color	Air		Water		Color	Air		Water	
	Contrast+	Rank	32 ft	64 ft		Contrast+	Rank	48 ft	80 ft
Fl. Orange	+1.20	1.0	1.2	2.2	Fl. Green	+0.82	1.2	2.1	1.9
Black	-0.89	2.2	1.8	1.2	Black	-0.89	2.3	1.1	1.2
White	+0.81	2.8	3.2	3.6	White	+0.81	2.6	3.4	3.2
Dark Gray	-0.54	4.0	3.8	3.0	Green	-0.77	3.9	3.5	3.7

+Contrast is calculated by the formula, $C = \frac{L_t - L_b}{L_b}$,

where L_t = luminance of the target area

L_b = luminance of the light gray background whose reflectance is 44%.

There were other, more subtle, differences however which were not expected and seem to relate to the direction of the contrast; that is, negative contrast targets appear to be more visible under water than equal contrast targets whose sign is positive. For example, the contrast in air for black calculates to a slightly greater value than for white, and the air judgments reflect this difference; black was judged slightly more visible on the average than the white. In the water, however, black is clearly superior to white at all viewing distances. Similarly, in air, gray is much less visible than white, in agreement with the contrast values; this difference is decreased at 32 ft in water and reversed with 64 ft of water. Also, fluorescent green, another positive contrast target, does not do as well as might be expected, although it is difficult to calculate its contrast without exact information on the activating energy reaching it through the water.

Formulae for predicting visibility from inherent contrast do not help in understanding this phenomenon. In air, judgments have generally shown positive and negative contrasts to be equally visible;[9] the water formulae show the reduction in visibility due to scattering and absorption but do not

differentiate between negative and positive under the same viewing conditions. Thus, for example, a black target whose inherent contrast with its background is -0.90 will be attenuated by a horizontal viewing path of 10 meters of water (with an alpha of .10) to a contrast of -0.33. However, the white target will suffer the same reduction and thus should be equally visible. Sample calculations are given for a simple contrast formula in Appendix A. All contrasts are severely attenuated by the water, some approaching the limit of visibility (.02) at the 80 ft viewing distance. This prediction agrees with the empirical data: the lower contrast targets at 80 ft were occasionally not visible during the La Chalupa dive.

The transmission of energy under water is always subject to more variables than those which the relatively simple visibility formula considers and prediction is precarious without detailed data on the absorption and scattering characteristics of the specific body of water. Nonetheless, the possibility that negative contrasts under water are superior to positive deserves study. This is of particular importance for signs and displays under water since the background color can be controlled.

One interesting example of the complexities that occur under water is the reduction with distance under water in relative visibility of the regular green on the light gray background. One would expect the visibility of green to remain high, since green wavelengths are readily transmitted by clear ocean water, and, in fact, calculations of brightness show an increase relative to the brightness of the gray background. However, since the green was originally darker than the gray and after transmission through water is more like the gray, the result is a loss of contrast and a consequent loss of visibility.

Another area not covered by visibility formula is the effect of color contrast, as distinct from brightness contrast. While the latter is generally much more important than the former, there is a decided advantage, in comparing two colors of the same brightness contrast, for the hue that differs most from its background hue. This factor will change with depth and distance of water as the wavelengths that penetrate become selected.

Fluorescent Colors

Finally, some caution must be advised in the use of fluorescent colors under water. Fluorescent colors have been shown to be much more effective than regular paints of the same color under almost all conditions of underwater viewing. Their effectiveness is due to the fact that short wavelength visible energy, which is generally well transmitted by the water, is converted to longer wavelengths to which the eye is more sensitive.* In the case of

**One condition was found in which fluorescents were no better than regular paints, i.e., incandescent light sources in very turbid water. In this case there was not enough short wavelength energy available to activate the fluorescence.* [2]

fluorescent orange, for example, the fluorescence is activated by the entire wavelength band from 400 to 540 nanometers, a condition which results in a great increase in the energy available in the longer wavelengths. The paints, however, are not as durable as some regular paints and the fluorescent material may flake off if not protected. Durability tests or protective coatings are advised if these colors are to be used under water for extended time periods.

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APPENDIX A: Sample Calculations for the Regular Paints of Contrast Attenuation in Water, Predicted for Conditions of this Study.

Distance in water (r)	Attenuation factor	C_r			
		Black	White	Dark Gray	Dark Green
0 (C_o)	1.0	-.886	.809	-.545	-.768
32' (9.75 m)	.296	-.262	.239	-.161	-.218
48' (14.63 m)	.161	-.143	.130	-.088	-.118
64' (19.50 m)	.087	-.077	.070	-.047	-.056
80' (24.38 m)	.047	-.042	.038	-.026	-.033

Contrast is calculated on the basis of the following formula, for a horizontal viewing path in the water.

$$C_r = C_o e^{-\alpha r}$$

where C_r = apparent contrast at a distance r

C_o = the inherent target contrast $\dfrac{L_t - L_B}{L_B}$

α = attenuation coefficient of the water

r = distance in meters

with α = .125, typical of Caribbean water.

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13. ABSTRACT

Judgments of the relative visibility of colors were made during the "La Chalupa" dive from the habitat located in 100 ft of Caribbean water. Judgments made with colored targets viewed against the water background were in agreement with previous studies; that is, bright colors were the easiest to see and dark colors disappeared the most readily. However, when the colors were viewed against a light gray background, dark colors were the most visible. It appears that negative contrast under water is superior to positive contrast of the same amount. In addition, small diurnal changes were found with green increasing in visibility and orange decreasing as the day wore on.

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